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Dale A. [illegible]eins and James C. Shampine

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NAVY CLOTHING AND TEXTILE RESEARCH UNIT
NATICK, MASSACHUSETTS

EVALUATION OF HEAT LOSS FROM NAVY DIVERS' WET SUIT

by

D. A. Reins and J. C. Shampine

Work Unit No.
523-003-01-03

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ABSTRACT

In a series of over 200 tests held at the Navy Clothing and Textile Research Unit (NCTRU), subjects wore standard, 3/16-inch, closed-cell, neoprene-foam, Air-Sea Rescue suits in water of 55, 45, and 35°F. These tests were designed to identify areas of the body where major heat losses occur. Other physiological parameters were monitored to assure the physical safety of test subjects while body temperature and metabolic rates were measured. Tests showed that the major area of heat loss is from the trunk area but fit of the suit is also important because up to 23% of the heat is lost through flushing of water into and out of the suit. Recommendations are made as to areas in which insulative values could be increased without hampering free movement of the wearer, and design modifications are suggested to limit free movement of water into and out of the suit.

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EVALUATION OF HEAT LOSS FROM NAVY DIVERS' WET SUIT

INTRODUCTION

The studies described in this paper were designed by Navy Clothing and Textile Research Unit (NCTRU) physiologists to identify the major areas of heat loss from subjects wearing wet suits and to produce data which can be used as a basis of comparison when improved models are designed. Testing was done on human test subjects exposed to water temperatures similar to those encountered when the suits are in use. Loss of body heat is a recurring problem among divers using the wet suits which the Navy calls Air-Sea Rescue suits. SCUBA divers around the world use these suits with minor variations. Most divers feel that the closed-cell neoprene foam used in these suits fails to insulate effectively and thus allows loss of body heat. Little information is available which confirms this belief or describes how and from what portions of the body heat is lost. Although this is primarily a problem of clothing design, physiological parameters were used as indices of exposure.

METHODS

The purpose of the tests was to identify the sources of heat lost from the body while the wet suit was being worn. Consequently, separate tests were conducted under various conditions. Results from the tests in which subjects were completely submerged were used as a maximum stress condition to which data on the other positions were compared. The other positions of test subjects were: (a) one arm kept out of the water and dry; (b) one leg remained out of the water and dry; and, (c) both legs and arms kept out of the water and dry. Water temperatures were 55, 45, and 35°F while air temperature was maintained at 100°F to minimize heat loss from the body member not under water. Relative humidity was not considered pertinent in these studies because the wet suit was impermeable to the air environment and evaporative heat loss was negligible.

Clothing worn for the test was standard Navy Air-Sea Rescue Kit (1) of 3/16-inch neoprene foam, including hood, gloves, and boots (Figure 1).

Thirty-one test subject volunteers, drawn at random from the test subject pool of the Army's Natick Laboratories, were used over a period of 10 months. All were of ages and sizes comparable to Navy personnel who would normally use this type of equipment.

Test subjects were used for 10 days at a time, because such a short training and testing period would not permit adaptation to temperature. Skreslet and Aarefjord report that adaptation to cold water takes 45 days and is labile because it disappears after 17 days of non-diving (2). A three-day training period was allowed, during which test subjects were

fitted with wet suits and taught to use a mask, snorkel, and SCUBA equipment. After three three-hour sessions all but one of the test subjects were familiar enough with the equipment and confident enough in it to take part in the test. (It was emphasized that test subjects were not being trained to be qualified SCUBA divers but only to be familiar enough with this type of equipment to participate in the test.) Those who volunteered to be test subjects were given a physical examination and certified as able to stand the stresses of these experiments.

PROCEDURE

Test subjects reported to the lab and rested upon a bed at least 15 minutes before their Basal Metabolic Rate (BMR) was determined. After the BMR the subjects provided a urine sample for urinalysis, stripped, and were weighed nude on a Toledo scale accurate to ± 10 gms.

Thermocouple leads, held in place by adhesive strips, were applied to the following 10 skin areas:

a.	Arch of foot	f.	Chest
b.	Calf of leg	g.	Upper arm
c.	Lateral thigh	h.	Lower arm
d.	Medial thigh	i.	Tip of middle finger
e.	Back	j.	Cheek

The rectal probe, made by placing a thermocouple inside a No. 16 soft rubber catheter, was inserted about 15 cm. into the test subject's rectum. Beckman skin electrodes were attached, three in a vertical row over the sternum for the recording of EKG, and two over the right intercostal space between the ninth and tenth ribs for the recording of respiration rate (3).

The wet suit was worn over swim trunks and test leads. After dressing, the test subject was taken to the pool area, and lead wiring, which ran from between the top and bottom parts of the wet suit, was attached to the connection console. After baseline readings were obtained, the subject adjusted his face mask, entered the water, assumed a reclining position upon a couch anchored to the bottom of the pool, took the mouthpiece, and started breathing air from the SCUBA. The exact times when the subjects began breathing SCUBA air and the pressures of the SCUBA tank were recorded. The amount of air used by the test subject was calculated from the difference in the reading taken at this time and the final reading from the pressure gauge. A standard SCUBA pressure gauge, readable to ± 25 lbs. pressure, was used. (Gauges were periodically checked for accuracy in the U.S. Army Natick Calibration Laboratory.)

Rectal temperature, skin temperatures, and weighted mean skin temperature (4) were recorded on an Esterline Angus 48-point programable recorder. Temperatures were monitored continuously every 90 seconds. Five-minute time periods were marked to coincide with the five-minute-interval recordings on the Beckman Type R Dynograph on which EKG, respiratory rate, heart rate, O_2 uptake, and CO_2 output were monitored continuously and on an expanded scale.

Oxygen uptake was measured by a Beckman Field Lab Oxygen Analyzer and the output recorded as described above. Room air was used to standardize the instruments reading at 20.9 percent O_2 and sensitivity of the output was adjusted to read 1 percent for each 5 mm pen deflection on the recorder. The high percentage of CO_2 in the expired air, as compared with that of the room air, caused the O_2 probe output to drift. The drift was corrected at each five-minute interval.

Expired air was analyzed for CO_2 by a Beckman (LB1) pickup. Output from this pickup was fed directly to the recorder through a CO_2 coupler. Sensitivity was adjusted to read 5 mm pen deflection for each percent CO_2 when a 4 percent CO_2, 96 percent O_2, certified-analysis, standard gas was used as a standard for CO_2 concentration, and room air for the zero set point. This instrument proved to be extremely stable in use and required very little attention, although zero set point was checked at the same check points used for the O_2 probe and the 4 percent CO_2 standard was introduced several times during each experiment to assure that the readings were within desirable limits of accuracy. Samples were also taken several times during the series and analyzed by the Schollander gas-analysis technique. These never varied more than $\pm$ 0.1 percent for either O_2 or CO_2, which further substantiated our belief in the reliability of the Beckman instruments.

Samples of expired air were pumped from under water to the measuring equipment by a Beckman micro catheter pump. This pump acted as a flow-limiting valve because the air under water was at a higher pressure than room air. All readings were made at room air pressure and temperature. The complete method of sampling is discussed in another paper (5).

After 30 minutes, or less if the subject felt conditions to be intolerable, the subject came out of the water and stood by the side of the pool for approximately 120 seconds while final readings were made. After he was disconnected from the console, he removed his wet suit, wiring harnesses, and swimsuit, and towelled himself dry. Then, his nude weight was again taken, total volume of the final urine sample was recorded, urinalysis repeated, and a final BMR taken. The subject was then told to dress and allowed to rest for a half hour before being dismissed.

After tests were completed, the parameters listed below were calculated.

1. Volume of air used (V_A) converted to room air pressure and temperature by the formula: $V_A = \frac{V_T}{P_r}\frac{T_R}{T_W}\Delta P = .91\,\frac{T_R}{T_W}\,\Delta P$

When:

$\frac{V_T}{P_r}$ = 0.91 for room pressure (P_r) or 14.7 psia and a SCUBA tank water volume (V_T) of 13.4 liters.

ΔP = change in pressure of the SCUBA tank (psi)

T_R = absolute temperature of the O_2 and CO_2 measuring instrument in the room (°C ABS)

T_W = absolute temperature of the water in the pool (°C ABS)

2. Volume O_2 used per hour as calculated from measured percent uptake, calculated by use of the formula:

$$V_{O_2} = \frac{0.36\,(K_{O_2}\,V_A)\,(P_B - P_{H_2O})}{T_R\,(ABS)\,\theta}$$

When:

V_{O_2} = Volume O_2 used per hour at standard temperature (T_{ST} = 0°C) and pressure (P_s = 760 mmHg) (liters/hour)

0.36 = Ratio of $\frac{T_{ST(ABS)}}{P_s} = \frac{273}{760}$ = .36°C ABS/mm Hg

K_{O_2} = percent O_2 uptake as measured

θ = Time (in hours) test subject was breathing from the SCUBA

P_B = Ambient barometric pressure (mm Hg)

P_{H_2O} = Partial pressure of water vapor (mm Hg) in the air sample (The air was considered saturated at the test water temperature)

T_R = Absolute temperature at the instruments in the room

3. Mean body temperature calculated from the formula (4):

$$T_B = 0.8T_C + 0.2T_S$$

When:

T_B = Mean body temperature °C

T_C = Core temperature (as measured rectally) °C

T_S = Weighted mean skin temperature °C

4. Change in body heat content as calculated from the formula:

$$\Delta Q = \frac{0.83W \quad \Delta T_B}{\theta A}$$

When:

ΔQ = Change in body heat content (K cal/hr/m^2)

0.83 = Specific heat of the human body (K cal/Kg ^oC)

W = Weight of subject (Kg)

ΔT_B = Change in mean body temperature as calculated by subtracting the final body temperature from the initial body temperature (^oC)

θ = Time subject was under observation (hours)

A = Area of body exposed in water (m^2)

5. Metabolic heat evolved, calculated by use of the formula:

$$Q = \frac{4.83\ (V_{O_2})}{A}$$

When:

Q = Metabolic heat evolved (K cal/hr/m^2)

4.83 = Relationship between O_2 uptake and heat evolved (K cal/ℓ O_2)(6)

The following formula summarized separate equations for respiratory heat loss. These equations yield: (a) the amount of heat lost by warming inhaled air to body temperature; (b) the amount of heat required to warm the water vapor of the inhaled air; and, (c) the amount of heat needed to saturate exhaled air by evaporation.

6. Combining the influence of the above effects on respiratory heat loss, we arrive at the equation (14):

$$Q_R = \frac{.000312\ V_A\ (34-T_{ai}) + 1.58\ (44-P_{H_2Oi})}{A}$$

When:

Q_R = Respiratory heat loss (K cal/hr/m^2)

V_A = Volume air (STP) used per hour (liters/hr)

T_{ai} = Temperature of air inhaled (^oC)

P_{H_2Oi} = Partial pressure of water vapor in inhaled air (mm Hg)

7. Total heat lost from test subject body surface is calculated from the formula:

$$\Delta Q_B = (Q + \Delta Q) - Q_R$$

When:

ΔQ_B = Heat lost from test subject body surface (K cal/hr/m^2)

Q = Heat evolved from ℓ O_2 metabolized (K cal/hr m^2)

ΔQ = Change in body heat content (K cal/hr/m^2)

Q_R = Heat lost by respiration (K cal/hr/m^2)

8. Since heat transmission characteristics of the wet suit material were known (15, 16), theoretical heat loss through the suit could be calculated when the mean skin temperature, water temperature and area exposed to the water were known by use of the equation:

$$Q_S = U \quad \Delta T$$

When:

Q_S = Calculated heat through the suit (K cal/hr/m^2)

U = Thermal conductance constant for material of which suit was constructed (12.4 K cal/hr/m^2/^oC)

ΔT = Difference between mean skin temperature of all test subjects and actual water temperature

9. Heat lost by flushing Q_F:

$$Q_F = \Delta Q_B - Q_S$$

RESULTS

Parameters of interest to this discussion are those concerned with the heat-conserving characteristics of the suits under test. For the purpose of these tests, parameters other than those needed to compute heat losses were necessary in order that test subjects would have the necessary surveillance to ensure their safety during periods of exposure. Also, the basal metabolism measurements taken before and after the actual tests indicated test subject apprehension, or lack of it, prior to the test exposure.

Oxygen consumption was used as a basis for calculating the amount of heat generated through metabolic processes (Table I), and the relationship between heart rate and O_2 uptake reported by other investigators (8, 9, 10, 11) seemed to be borne out in some instances but not in others. These observations have been covered more fully in another paper (20). NCTRU physiologists attribute at least some of the variability in metabolic heat production to the fact that groups of test subjects differed in their experience, as some were new recruits who had just finished basic training while others had been test subjects for over a year. The important point is that the heat losses per water surface area exposed remained relatively constant, as indicated by the small standard error (Table II), regardless of the metabolic responses of the test subjects.

Subjective observations based on test subject, personal, and other comments (13) indicated that much of the heat loss was due to flushing of water in and out of the suit. However, when the theoretical heat loss, as calculated from the known temperature difference between the skin of test subjects and the water by use of the coefficient of heat transfer known to apply to the wet suit material (15, 16), is compared with the heat loss as calculated from the experimental data (Table III), it is obvious that the greatest amount of heat loss is through the material, and flushing is of secondary importance.

It is also evident from data presented in Table III that the major portion of heat loss comes from the trunk region of the test subjects' bodies.

DISCUSSION

The increased metabolic rate indicated at 55°F and 45°F with one arm out of the water as compared with the other positions (Table I) is probably caused by the test subjects' sustained effort to maintain themselves in position. Also, the temperatures of the water were such that these suits were relatively comfortable to wear and allowed the test subjects to relax and attain a basal state while under observation in the other two positions. As water temperature decreased, the test subjects became less comfortable and could not attain a basal state when exposed to 35°F temperature.

The consistent heat loss as indicated by the small standard error may be attributed to two factors: (a) conduction of heat through the material (Table II); and, (b) flushing of water into and out of the suit which accounts for a greater percentage of the total loss in the partially submerged test subjects than in the completely submerged test subjects at 45 and 35°F. Statistical significance of the other two positions tested was so small that only the extremes are compared. Our finding that most of the heat loss is from the trunk area in these studies agrees with findings of others who describe the decrease in blood flow through the extremities of test subjects immersed in water (17, 18, 19). Beckman states that rate of heat loss from an immersed body is so rapid that the limit is primarily that imposed by the rate by which the blood transfers heat from the central core of the body to the skin (12). Therefore, the amount of heat loss ascribed to flushing would require movement of an extremely small quantity of water.

Data in Table II are reduced to a comparison of heat loss per unit area of exposure with the aqueous environment. Thus, if the amount of water flushing is the same and the amount of heat loss through the material of the suit is the same, heat loss in any position for the same temperature should be the same. Increased heat loss per unit of area exposed to the water, as indicated in Table II for the partially submerged position, is interpreted to mean that the major portion of heat loss is from the trunk area and a higher percentage of heat is lost from flushing in this position. This increased flushing loss results from the way in which the suits fit and shows a need for design improvement to allow changes in position without a concomitant increase in amount of flushing of water into and out of the suit.

As was expected, the greatest amount of heat loss was in 35°F water (Table I) with a mean value for all exposures of 326 K cal/hr/m^2. The flushing loss was only 23% (Table III) of the total heat loss in the worst instance. However, the discomfort caused by this small amount of water exchanged in this way was compatible with experience of NCTRU divers and with comments made by an ex-Navy diver (13).

CONCLUSIONS AND RECOMMENDATIONS

Evidence presented in this report indicates that a maximum of 23 percent (Table III) of the heat loss from the SCUBA suit is due to flushing and 77 percent to conduction through the suit material. Most of the heat lost through the material is from the trunk area, where flexibility is not much of a problem. An increased thickness of suit material and an increased effectiveness of the insulation itself in this area would conserve body heat and improve the comfort to the wearer without hampering effective movement.

Since the flushing represents a significant loss as well as discomfort, some change in suit design is needed to correct heat loss from this source, because suits which fit tightly enough to prevent a flushing action of the water limit freedom of action of the wearer and also tend to be uncomfortable. If, however, the suit were lined with a non-absorbing synthetic fleece, a fit could be attained which would limit motion of water without affecting the activity of the wearer.

Design engineers may prefer to solve the problem by designing a one-piece ensemble which could be entered by means of appropriately placed, waterproof zippers. Another possiblity which should be considered is the incorporation of a highly elastic band to be fitted around a person's neck. Such a band would, without restricting the activity of the wearer, decrease the ease with which water is able to move in and out of the suit. On the other hand, any pressures, however slight, from an elastic worn for an extended period of time, tend to limit circulation and cause discomfort. Consequently, this type of solution may not be feasible from a standpoint of comfort unless clothing engineers can resolve this problem. Any modification which will limit movement of water in and out of the suit and decrease the quantity of heat loss from the trunk area while allowing freedom of movement for the wearer will be an inprovement. Modifications, as indicated above, in insulating values and in limiting movement of the water into and out of the suit are necessary before further testing is justified.

APPENDIX A. ILLUSTRATIONS

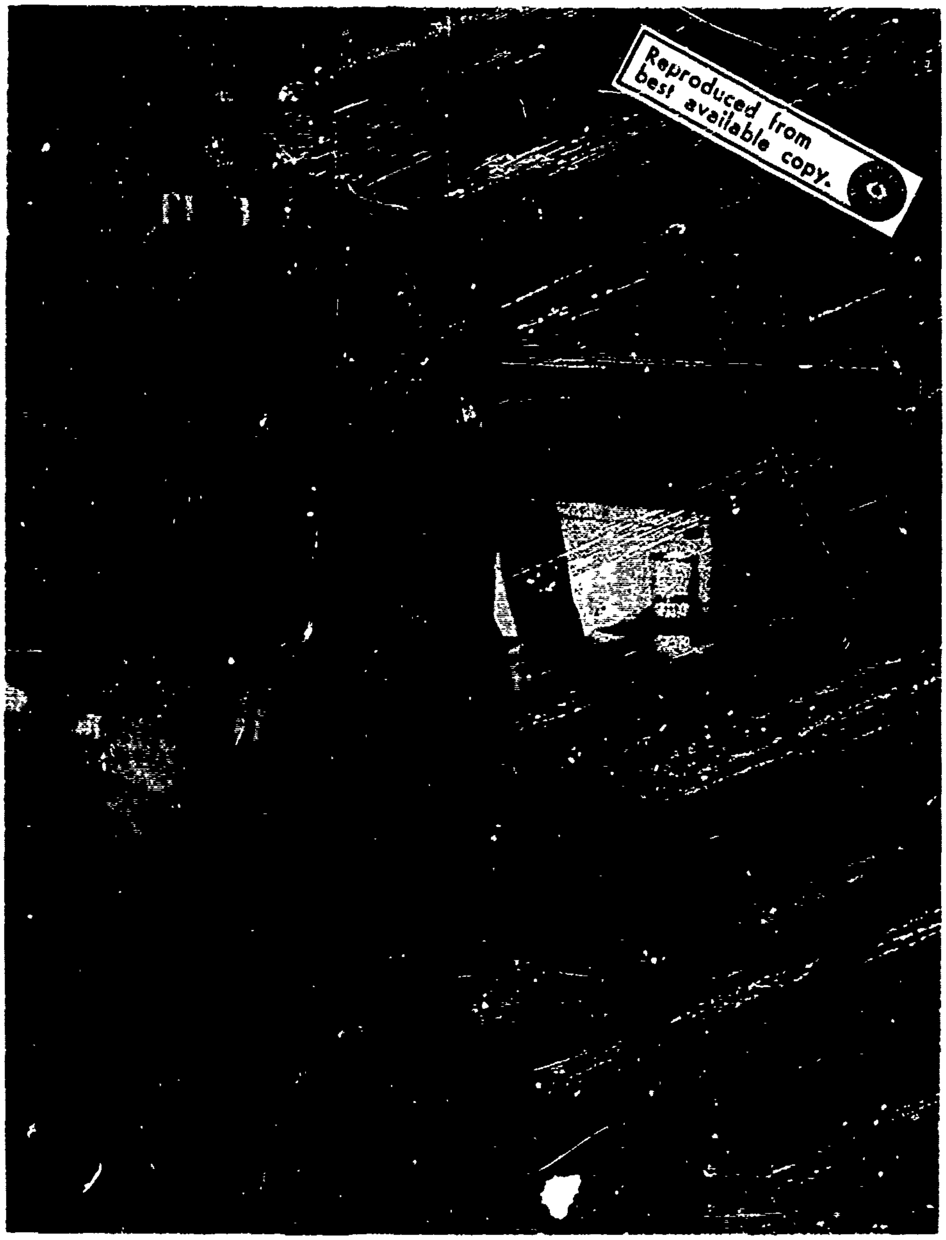

Figure 1. Test subject in the ASR suit. He is carrying the thermocouple, EKG and respiration leads and is ready to leave the dressing room to go to the pool area.

APPENDIX B. TABLES

TABLE I. METABOLIC HEAT FROM O_2 UPTAKE (K cal/hr/m^2)

Position of Test Subjects	55°F Mean	55°F Standard Error	55°F N	55°F P	45°F Mean	45°F Standard Error	45°F N	45°F P	35°F Mean	35°F Standard Error	35°F N	35°F P
1. Submerged	79	±4	21		106	±5	19		137	±19	9	
2. Left Arm Out	90	±4	16	.05	118	±6	27	.15	102	± 3	13	.05
3. Left Leg Out	77	±5	17	.85	95	±7	16	.30	108	±10	9	.25
4. Both Arms & Legs Out	76	±6	4	.85	107	±8	14	.90	100	± 8	7	.15

Metabolic heat calculated from O_2 uptake (K cal/hr/m^2).

Means of heat evolved with standard error and number of tests upon which the means are based. Data from Position 1 are taken as control and other data are compared with it. Position 2 required effort which is reflected by significantly increased O_2 uptake except in 35°F water. Test subjects used in the 35°F-water part of the test showed much greater individual variation, and the test subjects used for the left-arm-out portion happened to be experienced test subjects maintaining a lower metabolic rate than the others. However, this variation in O_2 usage did not change the overall picture of heat loss (Table II) and the amount of heat loss by these subjects is comparable to the others.

TABLE II. HEAT LOSS FROM BODY SURFACE (K cal/hr/m^2)/BODY AREA EXPOSED TO WATER

Postion of Test Subjects	55°F Mean	55°F Standard Error	N	P	45°F Mean	45°F Standard Error	N	P	35°F Mean	35°F Standard Error	N	P
1. Submerged	200	±11	21		225	±17	18		317	±34	8	
2. Left Arm Out	198	±14	16	.90	232	± 6	27	.25	284	± 7	14	.25
3. Left Leg Out	196	± 9	17	.85	255	±16	16	.95	326	±21	9	.85
4. Both Arms & Legs Out	238	±41	4	.35	296	±18	14	.15	378	±15	7	.15

Means of heat loss (K cal/hr/m^2) standard error, and number of tests from which data were used are presented. Data taken from Postion 1 are used as a standard with which the other positions are compared. Statistical significance of variation at any position is small and the indication that more heat is lost when test subjects were in Position 4 supports the belief that the primary source of heat loss in these tests was from the trunk area of the body whether from conduction through the suit material or from flushing of water in and out of the suit.

TABLE III. HEAT LOSS SUMMARY

	POSITION 1			POSITION 4		
	55°	45°	35°	55°	45°	35°
Near Skin Mean Skin Temperature (°C)	26.8	24.8	23.8	30.8	27.9	25.0
ΔT °C	14.1	17.6	22.1	18.0	20.6	23.4
Area Exposed to Water Mean Body Area (m^2)	1.84	1.84	1.85	1.38	1.30	1.42
Calculated Heat Loss Through Suit (K cal/hr/m^2)	174	218	274	223	256	290
Measured Heat Loss (K cal/hr/m^2)	200	225.	317.	238.	296.	378.
Flushing Heat Loss (K cal/hr/m^2)	26	7	43	15	40	88
Percent Loss Due to Flushing	13	3.1	13.6	6.3	13.5	23.3

Material of Suit K = .04 BTU/hr/ft^2/°F
U 3/16" suit = 12.4 K cal/hr/m^2/°C
Position 1 represents the test subject completely submerged.
Position 4 represents the test subject with both arms and legs kept out of the water and dry.

Table III presents a summary of heat loss, computed from experimental data and comparison of theoretical heat loss by conductivity of the suit material (12.4 K cal/hr/m^2/°C) with the total heat loss/unit area exposed to the water. The percent of the difference between measured and calculated heat loss may be ascribed to flushing and the increased amount of flushing indicated by data from the partially submerged position at 35°F may be explained by (a) the position causes the suit to gape at the neck allowing water to move in and out more freely, and (b) test subjects in 35°F water were shivering violently by the end of the 30-minute test period. This involuntary activity also increased flushing due to body movements.

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